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LETTER

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Relationship between solar wind dynamic pressure and amplitude of geomagnetic sudden commencement (SC)

Tohru Araki^{1*} and Atsuki Shinbori²

Abstract

The local time variation of geomagnetic sudden commencements (SCs) has not been taken into account in the Siscoe's linear relationship which connects the SC amplitude with the corresponding dynamic pressure variation of the solar wind. By considering the physical background of SC, we studied which local time is best to extract the information of the solar wind dynamic pressure and concluded that the SC amplitude at 4–5 h local time of middle- and low-latitude stations most directly reflects the dynamic pressure effect. This result is used to re-check the order of magnitude of the largest 3 SCs observed since 1868.

Keywords: Geomagnetic sudden commencement, Solar wind dynamic pressure, Local time variation, Siscoe's relationship, Largest sudden commencement

Introduction

The geomagnetic sudden commencement (SC) tends to be considered as a simple compression of the magnetosphere. Although the primary source of SC is the magnetopause current (MC) increase due to the enhanced dynamic pressure (P_D) of the solar wind, various electric currents flowing in the wide regions of the magnetosphere, ionosphere and conducting earth contribute to the disturbance field of the SC observed in the magnetosphere and on the ground. Each current changes rapidly in a short time (~ 10 min.), and the resultant magnetic field shows a complex global distribution depending upon local time and latitude. By analyzing the global distribution of the waveform and amplitude of SCs, we can deduce where and how the electric currents are induced. Thus, the SC provides a good probe to study the transient response of the system composed of the earth, ionosphere and magnetosphere. A physical model of SC is presented in Araki (1977, 1994).

The SC has great effects on acceleration of the radiation belt particles. The CRRES satellite observed an

instantaneous formation of the inner radiation belt during an SC on March 24, 1991, at 2.6 Re around 3 h LT. It detected a drift echo event of high energy particles, a sharp pulse of the magnetic field with 130 nT amplitude and an associated bipolar electric field pulse of 80 mV/m peak-to-peak amplitude (Blake et al. 1992; Wygant et al. 1994). A computer simulation by Li et al. (1993) shows that a strong magnetopause compression occurred at 15 h LT and a produced hydromagnetic pulse propagated tail-ward accelerating magnetospheric particles to form the inner radiation belt which lasted nearly 1 year. The amplitude of the electric field pulse reached several hundred mV/m in the dayside magnetosphere (Gannon et al. 2005). An analysis of ground geomagnetic data was made by Araki et al. (1997). This SC taught us an importance of the magnetospheric compression on behaviors of the radiation belt.

Since the SC is caused by a sudden increase in the solar wind dynamic pressure associated with the interplanetary shock (IPS) or discontinuity (DC), we can obtain information about the IPS and DC from observations of SCs. In the pre-satellite era, the SC was the only way to know about IPS and DC. The SC plays an important role in the theory of magnetic storms by Chapman and Ferraro (1931, 1932, 1933).

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Siscoe et al. (1968) firstly proposed a linear relationship between the jump of the square root of P_D and the SC amplitude (ΔH) as

$$\Delta H = C \Delta(P_D^{0.5}) = C \Delta[(NmV^2)^{0.5}] \quad (1)$$

where N , m and V are the number density, particle mass and velocity of the solar wind. The mass of the solar wind particle is taken as $m = 1.16 m_p$ (m_p : proton mass), assuming 4 % abundance of helium ions. The constant, C , is given by $C = k f \alpha$, where k is the proportionality constant and f (assumed as unity) is related to the mode of the interaction of the IPS or DC with the magnetosphere. Physically, C means SC amplitude normalized by solar wind dynamic pressure variation.

A time-varying external magnetic field induces electric currents in the earth, which enhance the magnetic field above the surface of the earth. This induction effect is given by α , which is usually taken as 1.5.

Siscoe et al. (1968) experimentally determined the proportionality constant k . After them, many workers have derived the value of k . It can be derived also from P_D dependence of the Dst index (Verzardi et al. 1972; Su and Konradi 1975; Araki et al. 1993). The derived k values are summarized in Table 1 of Araki et al. (1993) in which k values are mostly between 8 and 12 nT/nPa^{0.5}. Exceptions are Verzardi et al. (1972) ($k = 18.4$), Su and Konradi (1975) ($k = 22.6$) and Smith et al. (1986) ($k = 14$). Mead (1964) also showed higher k value, 17.4, but it is a theoretical estimate for the vacuum magnetosphere.

Shinbori et al. (2009) analyzed sudden H-component increase events (not limited to registered SCs) by using the SYM-H index and obtained 19–20 nT/(nPa)^{0.5} for the constant C . This is for the amplitude averaged over local time and equivalent to $k = 12.7$ –13.3 if we assume $f = 1$ and $\alpha = 1.5$. Luehr et al. (2009) obtained similar C values, 18–20 nT/(nPa)^{0.5} from the analysis of SCs observed by the CHAMP satellite above the ionosphere in the nighttime. This is also equivalent to $k = 12.0$ –13.3 for (α , f) = (1.5, 1).

As will be described in detail later, the amplitude of SC shows a clear LT dependence. In middle latitudes, it takes the maximum around the mid-night and the second maximum in the post-noon. This means that the disturbance field of SC is modified by the secondary induced currents. It is important to consider how to extract the direct effects of the solar wind dynamic pressure from the modified amplitude of SC when the Siscoe's formula is applied. No one has paid attention to this point so far.

In this paper, we study which local time is best to estimate the dynamic pressure effect from the observed SC amplitude.

Background model of SC

Here we summarize the physical model of SC described in Araki (1977, 1994), which is necessary to consider the subject of this paper.

When the magnetosphere is suddenly compressed by an enhanced P_D of the IPS or DC, the dawn-to-dusk (eastward in dayside) magnetopause current J_{MC} increases to resist the compression by the sunward $J_{MC} \times B$ force where B is the northward magnetic field of the earth. The effect of the compression is transmitted by the compressional hydromagnetic (HM) wave propagating toward the earth in the dayside magnetosphere. A dusk-to-dawn (westward in dayside) electric current J_{WFC} flows along the wave front of which $J_{WFC} \times B$ force compresses the magnetospheric plasma toward the earth. The northward magnetic field increases in the current loop composed of the eastward J_{MC} and westward J_{WFC} .

In the initial stage of the magnetospheric compression, a pair of field-aligned currents (FACs) is formed by the dusk-to-dawn electric field, which drives the J_{WFC} . It flows down to the polar ionosphere in the afternoon and flows up from the ionosphere in the morning side. The FACs produce twin vortex-type ionospheric currents (ICs). The afternoon vortex expands to the dayside equator where the IC flows westward.

In the second stage after the passage of the compressional HM wave front tail-ward, the dawn-to-dusk electric field is enhanced by the enhanced magnetospheric convection in the compressed magnetosphere. This electric field produces the FACs and ICs, which flow in the opposite direction of the initial stage currents.

On the ground, two pulses called the preliminary impulse (PI) and main impulse (MI) successively appear. Each of them is caused by the initial- and second-stage electric current system. The SC is characterized by this switching from PI to MI corresponding to switching of the magnetospheric electric field from the dusk-to-dawn to dawn-to-dusk direction. This is the general and fundamental response of the magnetosphere to its sudden compression. Computer simulations show results consistent with this picture (e.g., Fujita et al. 2003a, b).

The disturbance field of SCs observed on the ground is expressed as

$$D_{sc} = DL_{MI} + DP_{PI} + DP_{MI} \quad (2)$$

where DL means a disturbance field dominant in low latitudes, and DP is dominant in polar regions. The main source of the DL-field is the magnetopause current (MC) enhanced during the sudden compression of the magnetosphere. The DP-field is caused by the FACs and the FAC-produced ICs described above. Currents induced in the earth enhance both DL- and DP-fields above the

earth. Note that the PI has not the DL part. It means that the PI has a pure polar origin.

The MI of which amplitude we are discussing in this paper consists of the DL_{MI} - and DP_{MI} -field. Although the DL_{MI} is produced directly by the enhanced solar wind dynamic pressure (P_D), the MI is modified by the secondarily induced FAC and IC. This modification expressed by DP_{MI} is the main cause of the LT variation of SC. In order to extract the pure P_D effect on SC, we have to minimize the DP_{MI} -field.

The FAC and IC responsible for the DP_{MI} -field are illustrated in Fig. 1 (Araki et al. 2009). The FAC goes down into the ionosphere in the dawn side and goes up from the ionosphere in the dusk side. The FAC-produced IC shows the larger current vortex in the afternoon side, which flows eastward in the dayside equator. This current system plays an important role also in Pc5 magnetic pulsations (Motoba et al. 2002).

Analysis

Left two panels of Fig. 2 which is also from Araki et al. (2009) show the averaged LT variations of the amplitude of the SC-MI observed at Memanbetsu (35.1° geomagnetic latitude) for the summer and winter season. Right panels indicate calculated LT variations of the DP_{MI} -field at 35° geomagnetic latitude, which are produced by the FACs and the FAC-produced ICs excited during SC (Kikuchi et al. 2001). The realistic conductivity distribution is given on the thin shell ionosphere. We see that both observation and calculation show the similar LT variation in summer, the maximum amplitude near midnight, the minimum at 7–8 LT and the second maximum in 13–16 h LT. In winter, the LT of the observed maximum shifts to 3 h LT, but the overall pattern of the observed and calculated LT variation is similar. We can say, therefore, that the LT variation of the SC amplitude is produced by the assumed FACs and the FAC-induced ICs. We consider that the winter maximum might shift to midnight if we can analyze a larger number of SC events.

The right panels show that the night maximum is due to a pair of FACs (Araki et al. 2006). The ionospheric

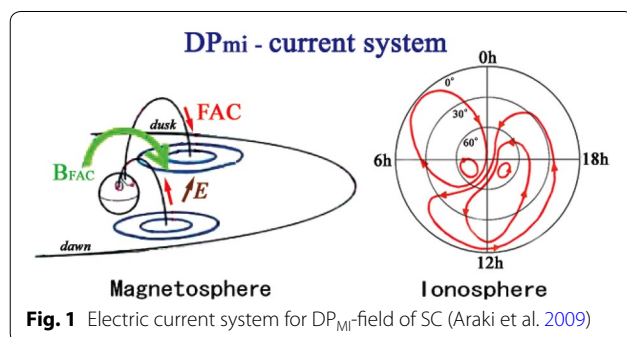
currents are small there because the ionospheric conductivities are very low in the nighttime. In the dayside, the ionospheric current of polar origin flows eastward producing a positive H-component, but it is reduced by a negative (southward) field of the FACs and the second peak appears in the early afternoon.

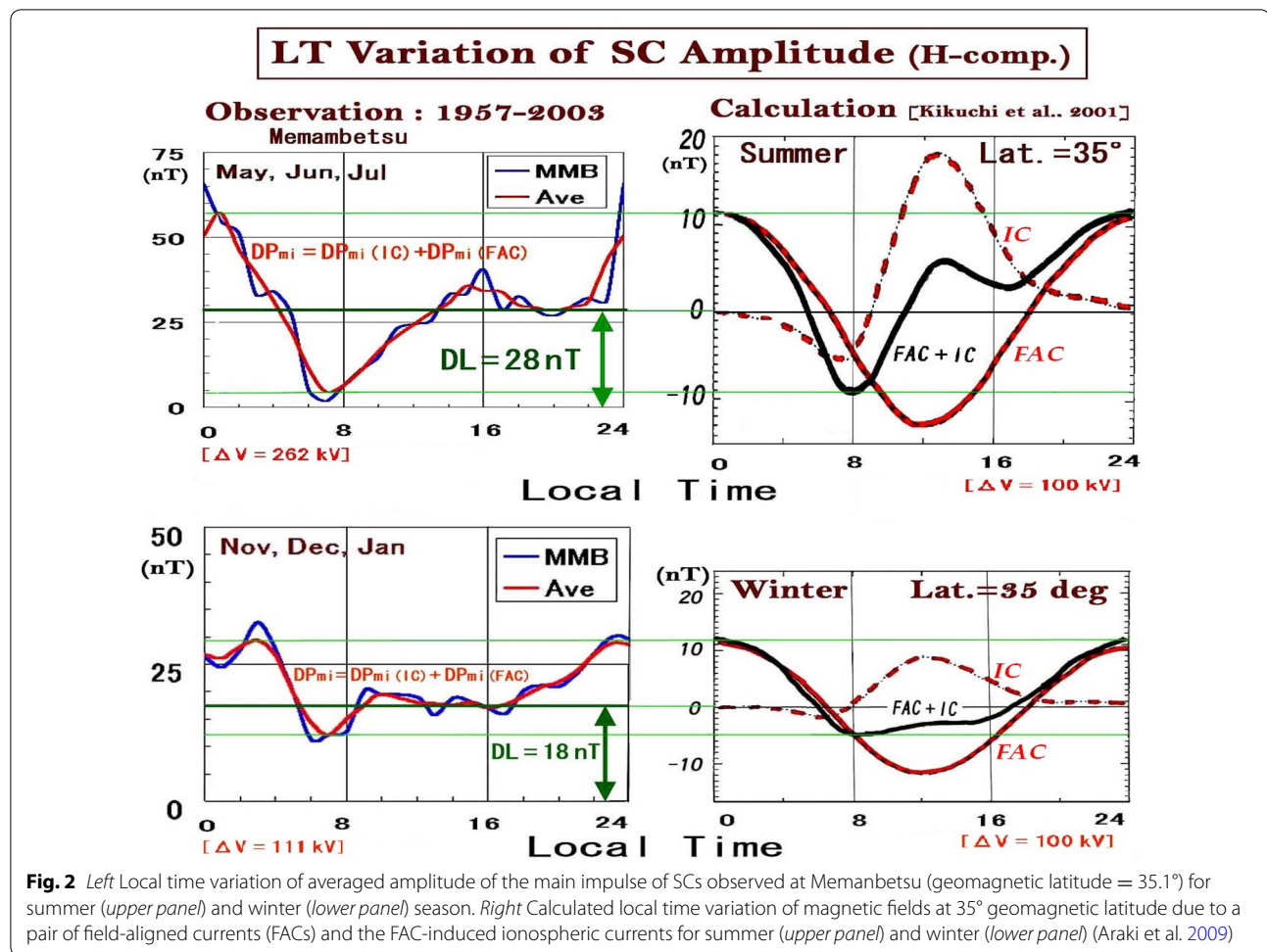
The scale of the ordinate of the left two panels of Fig. 2 is adjusted so that the observed maximum and minimum of the amplitude coincide with those of the calculated LT variations of the left panels. Then, we could know the zero level of the observed DP_{MI} -field from the zero level of the calculated LT variations. This zero level indicates the DL_{MI} -field, which is indicated in the figures as 28 nT for summer and 18 nT for winter. They are observed around 4 and 13 h LT in the summer and 5 and 13 h LT in the winter.

The description above suggests that we should use the SC amplitude observed at 4–5 h LT to study corresponding dynamic pressure variations in both summer and winter seasons. Another LT for the zero DP_{MI} level (around 13 h for both seasons) is not appropriate because both IC and FAC are relatively large and LT of the zero DP_{MI} is easily changed.

Shinbori (private communication) derived the averaged LT variation of the constant C , of Eq. 1 for five low and middle latitude stations, Yap (YAP; geomagnetic latitude = 0.4°), Guam (GAM; 5.5°), Okinawa (OKI; 15.1°), Kakioka (KAK; 27.1°) and Memanbetsu (MMB; 35.1°). Necessary dynamic pressure data are taken from the CDAW Web site. The results are shown in Fig. 3. In order to obtain smoother curves of the LT variation, the event to be analyzed was not restricted to the registered SCs but expanded to general sudden H-component increases as described previously. He picked up sudden increases in the SYM-H index by 5 nT in 10 min. and checked corresponding P_D increase. As a result, it becomes possible to analyze large number of the event. (Event number and data period) of each station are (3508, 1996-1-5–2010-10-31) for MMB, (3528, 1996-01-05–2010-10-31) for KAK, (2024, 1996-04-27–2008-10-29) for OKI, (3096, 1996-01-05–2008-12-31) for GAM and (1976, 1996-03-19–2008-08-16) for YAP (Shinbori et al. 2012).

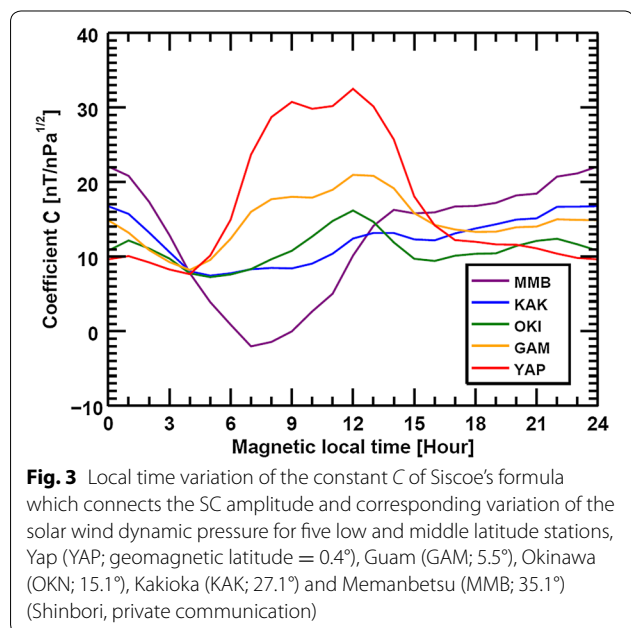
The LT variation of C (SC amplitude normalized by solar wind dynamic pressure variation) at MMB and KAK takes the maximum and the second maximum around midnight and noon, respectively. This is similar to Fig. 2 for MMB. At the three lower latitude stations, the midnight maximum is reduced and the noon peak becomes the maximum. The noon maximum is especially large at YAP near the dip equator. This is due to the eastward IC enhanced by the enhanced Cowling conductivity and is called the equatorial enhancement of SC. The instantaneous penetration of a magnetospheric electric field to the dayside equator is discussed by Kikuchi et al. (2008).





In Fig. 3, the LT variation of C varies greatly from station to station. This means that the contribution of the FAC and IC to the DP_{MI} -field depends much on local time and latitude. The C values of the five stations, however, become almost the same at 4 h LT. It indicates that the resultant contribution of FAC and IC to the DP_{MI} -field is small around this local time, and the amplitude shows the nearly pure DL-field. In the right panels of Fig. 2, we see that the DP_{MI} -field takes zero value in 4–5 h LT.

More accurately, however, the DL-field should decrease slowly with increasing latitude from the equator because it primarily originates in the magnetopause current. If it follows to the cosine law of latitude, the ratio of the DL_{MI} of YAP, GAM, OKI, KAK and MMB should be 1.0, 0.99, 0.96, 0.89 and 0.81 of that of the equatorial station, respectively. If we check the C values at 5 h LT, Fig. 3 shows C 10.1, 9.6, 7.3, 7.5 and 3.9 in the order of the station above, respectively. It decreases with increasing latitude, but the order of OKI and KAK is



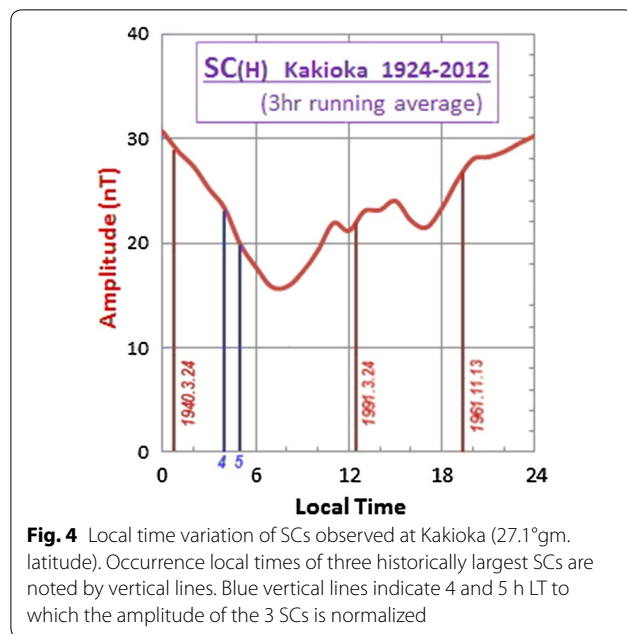


Fig. 4 Local time variation of SCs observed at Kakioka (27.1°gm. latitude). Occurrence local times of three historically largest SCs are noted by vertical lines. Blue vertical lines indicate 4 and 5 h LT to which the amplitude of the 3 SCs is normalized

reversed and the variation is larger than what is expected from the cosine law. We consider that this deviation is caused by the different LTs for the zero DP_{MI} -field at different latitudes. Tsunomura (1998) and Shinbori et al. (2009, 2012) made detailed analyses on the LT and latitudinal variation of the SCs and the sudden H-component increase events.

Araki (2014) surveyed large amplitude SCs observed since 1868. Only 3 SCs have the H-component amplitude larger than 200 nT at Colaba (gm. latitude 10.5°)-Alibag (10.3°) and Kakioka. The largest SC occurred on March 24, 1940, of which amplitude was 310 nT at Alibag. It was saturated at Kakioka but larger than 273 nT. The second and third largest SCs occurred on November 13, 1961, and March 24, 1991, with amplitude of 220 and 202 nT at Kakioka, respectively.

Figure 4 shows the averaged LT variation of the SC amplitude at Kakioka. The occurrence of LTs of the three largest SCs mentioned above is indicated by brown vertical lines. We normalized the amplitude of them to 4 and 5 h LT and showed the result in Table 1. We see that the first rank is still kept by the 1940 SC, but the 1991 SC takes the second rank.

From Eq. 1, the dynamic pressure behind the shock or discontinuity, P_{D2} , is given by

$$P_{D2} = \left[\Delta H / C + (P_{D1})^{0.5} \right]^2 \quad (3)$$

where P_{D1} is P_D in front of IPS or DC. According to Fig. 3, the C value of Kakioka is not much different at 4 and 5 h LT ($C = 8.5$ – 9.0). If we assume $C = 9$ nT/(nPa)^{0.5}, $P_{D1} = 2$ nPa and $\Delta H = 220$ nT (ΔH of 1940 SC

Table 1 Normalized amplitude (ΔH) of three largest SCs

Date: UT	1940.3.24 14:1506	1961.11.13:1023	1991.3.24:0341
ΔH : observed	273 nT<	220 nT	202 nT
ΔH : normalized to 4 h LT	220 nT<	196 nT	219 nT
ΔH : normalized to 5 h LT	189 nT<	169 nT	188 nT

normalized to 4 h LT), P_{D2} becomes 668 nPa. As discussed in Araki (2014), the nonlinear effect for a stronger magnetospheric compression will request larger P_{D2} . On the other hand, the induction effect of the earth current might request smaller P_{D2} , because of larger enhancement of SC amplitude due to stronger induced current. We need more quantitative analyses of these two competing effects.

Discussions

The analyses above are based upon geomagnetic data from the east Asian longitudes. Here we check whether the SC amplitude observed in other longitudes indicates a similar LT variation.

More than 60 years ago Ferraro and Unthank (1951) studied the LT dependence of hourly amplitude of 48 SCs at six stations, Cheltenham for which geomagnetic (latitude, longitude) is (48.5°, 354.6°), Tucson (39.6°, 316.8°), San Juan (27.9°, 6.6°), Honolulu (21.6°, 270.3°), Huancayo (−2.0°, 357.0°) and Watheroo (−40.0°, 189.2°). They found that Huancayo near the geomagnetic equator behaved very differently from the other five stations in low and middle latitudes. The mean amplitude showed a high maximum around noon, a secondary maximum about 1 h and the minima about 4 and 23 h LT. The equatorial station YAP used in our analysis shows the very similar LT variation of the normalized amplitude of sudden H-component increases (see, Fig. 3). Sugiura (1953) analyzed a larger number of SCs at Huancayo and obtained the similar LT variation. Shinbori et al. (2009) examined LT variations of PRI (preliminary reverse impulse) of SC in different longitudes. Two stations near the dip equator, Pohnpei (dip = 1.0, geomagnetic longitude = 229.4) and Ancon (1.4, 354.7), indicate similar LT variations, but the LT variation of Santa Maria (−34.4, 13.3) in the South Atlantic Anomaly region is quite different from that of Okinawa (38.0, 13.3) which was chosen for comparison.

Ferraro and Unthank (1951) also obtained the LT variation of 55 SCs and 46 SIs averaged over the five low and middle latitude stations mentioned above. It shows a maximum at 22–0 h, a second maximum around 14 h and a minimum at 7 h LT. This behavior is very similar to what is seen at Memanbetsu (Fig. 2) and Kakioka (Fig. 4). Later Russell et al. (1992) checked 18

SCs observed at Honolulu, Tahiti (-15.0° , 285.5°), San Juan and Midway (25.0° , 250.1°) during the northward IMF and found that the normalized amplitude shows the maximum and a second maximum near noon and midnight, respectively, and the minimum and a second minimum at 6–8 and 16 h, respectively. The results were confirmed by a similar analysis on 14 SCs (Russell et al. 1994a). Russell et al. (1994b) also studied 7 SCs at the same stations during the southward IMF. The normalized amplitude showed the maximum in midnight and the minimums near 6 and 16 h LT. Clauer et al. (2001) found an SC with the largest amplitude in midnight during a strong northward IMF turning and analyzed it as a special event. Although there is a discrepancy on IMF dependence of nighttime amplitude, above description indicates that the LT variation of SC amplitude does not depend much on longitude except the South Atlantic anomaly region. However, number of SCs and SIs used in these analyses is too small, and the amplitude is averaged over several stations except Sugiura (1953) and Shinbori et al. (2010). When we determine the best local time of a particular station to apply Eq. 1, more accurate LT variation of the SC amplitude at the station should be derived by using plenty of data as is done in this analysis.

Conclusion

The linear relationship that connects the SC amplitude ΔH with corresponding variation of the solar wind dynamic pressure P_D (Siscoe et al. 1968) was reconsidered. The most important point is that the LT variation of ΔH has not been taken into account in the Siscoe's relationship. This LT variation is produced by the field-aligned and ionospheric currents (FACs and ICs), which are secondarily induced during SC. The consideration based upon the physical model of SC (Araki 1977, 1994) leads to the conclusion that ΔH observed at 4–5 h LT at low and middle latitudes is least contaminated by the FAC and IC and well reflects the direct effect of the P_D variation.

The amplitude of the three largest SCs since 1868 reported by Araki (2014) are re-checked by taking the LT variation into account. The largest SC occurred on March 24, 1940, still keeps the first rank. The normalized ΔH to 4 h LT is 220 nT at Kakioka (geomagnetic latitude = 27.1°), which requests the P_D increase from 2 to 668 nPa if the linear relationship is still applicable.

Authors' contributions

Principal part of this work is done by TA. AS provided Fig. 3 and joined in the discussion. Both authors read and approved the final manuscript.

Authors' information

Tohru Araki is currently retired, but is a Professor Emeritus of the Graduate School of Science at Kyoto University and used the facilities of the

Department of Geophysics of the Graduate School of Science for his research work in this paper.

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We used the lists of SC at Kakioka and Memanbetsu prepared by Kakioka Geomagnetic Observatory. The SYM-H index was taken from WDC for Geomagnetism, Kyoto. The solar wind data were obtained from the IMP-8, ACE and Wind observations through the CDAW Web site (<http://cdaweb.gsfc.nasa.gov>). Geomagnetic data of the 5 stations are obtained from the Circum-Pacific-Magnetometer-Network (CPMN) (Yumoto and CPMN Group 2001) and National Institute of Information and Technology (NICT) Space Weather Monitoring (NSWM) (Kikuchi et al. 2008). Efforts for the observations and compilation of the data are highly appreciated. We also used the IUGONET data analysis tool (Tanaka et al. 2013) to calculate the C values.

Competing interests

There is no financial and non-financial competing interest exists in my interpretation of data or presentation of information, which may be influenced by my personal or financial relationship with other people or organizations after the publication of the manuscript.

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